Low-noise, Low-dark-current GaN Diodes for UV Detectors

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ABSTRACT

We report mesa-isolated Schottky barrier photodetectors fabricated on *n*-GaN. Single-element detectors were constructed from nitride epilayers grown by gas source molecular beam epitaxy (GSMBE) on Si(111). Chlorine-based reactive ion etching was used to form two-level mesas. The detectors were front-illuminated through 100 Å Pd semitransparent Schottky contacts on the upper mesas; ohmic contact on the lower mesas was made using standard Ti/Al/Ti/Au metallurgy. Silicon dioxide grown by plasma-enhanced chemical vapor deposition provided both surface passivation and electrical isolation. The dark current of an $86 \times 86\ \mu m^2$ single-element detector is 2.10×10^{-8} A/cm^2 at –2 V bias, and the zero-bias noise power density at 1Hz is as low as 9×10^{-29} A^2/Hz. In addition, we present preliminary results for *p-n* diodes fabricated from epilayers grown on sapphire. The dark current of a $50 \times 50\ \mu m^2$ single-element detector is 1.6×10^{-6} A/cm^2 at –2 V bias.

INTRODUCTION

Ultraviolet (UV) sensors for space astronomy have requirements distinct from those for industrial or military applications. First, they must be insensitive to light at optical wavelengths (commonly referred to as being solar blind), because, for example, astronomical objects often emit 10^4–10^8 visible photons for every UV photon[1]. These detectors are further required to generate as little noise and dark current as possible, since noise arising from the background often dominates in faint UV observations. Detector arrays must be addressed using low-noise readout techniques and they must be resistant to the effects of operation in space.

With their wide bandgaps, high thermal conductivities, chemical inertness, and radiation hardness, UV detectors implemented in GaN, AlN, and their alloys offer significant potential for solar-blind UV detectors capable of operating at high temperatures and in hostile environments. Device quantum efficiencies of (Al)GaN-based detectors are potentially several times greater than those of competing UV detector technologies[2].

In the last several years, nitride-based solar-blind UV detectors have made the transition from theoretical interest to practical application. While the vast majority of these detectors were fabricated from epilayers grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD), only a few utilized Si as the substrate and only a few grew epilayers by molecular beam epitaxy (MBE)[3-6]. Nevertheless, the use of silicon offers many benefits: large-area, low-cost, highly perfect substrates are readily available, a very sophisticated backside process technology has been developed over many years, and thermal expansion mismatch between detector arrays and readout electronics would be mitigated. In this work we describe GaN Schottky barrier diodes grown on Si(111) substrates by gas-source molecular beam epitaxy (GSMBE). These diodes exhibited extremely low reverse bias leakage currents and record low noise for GaN Schottky diodes on silicon. In addition, we present results for *p-n* diodes fabricated from epilayers grown on sapphire by GSMBE.

EXPERIMENT

The GaN/Si(111) detector structure consisted of a ~0.04 μm AlN buffer layer and a ~1.5 μm thick *n*-GaN layer grown on 2 inch diameter *p*-type Si(111) substrates by GSMBE[7]. The growth apparatus was equipped with a gas injector and a high-temperature substrate heater. Uncracked ammonia, used as a source of nitrogen, was injected into the growth chamber at a flow rate of 10–20 sccm. Elemental Al and Ga were used as group III sources. Epitaxial growth was performed at a substrate temperature of 760–780 °C, and the temperature was monitored using pyrometer interferometry. The Si surface was prepared prior to growth using a two-step etching procedure described previously[8].

Epitaxial growth started with the deposition of ~40 nm thick AlN buffer layer. The AlN buffer layer was found to be important in achieving high quality growth of wurtzite GaN on Si(111). Pure two-dimensional (2D) growth mode and smooth surface of AlN were evident from the streaky RHEED pattern. The deposition of GaN initially started in a three-dimensional mode, as indicated by a spotty RHEED pattern, and gradually transitioned into a pure 2D growth mode. The transition took place for a GaN thickness of ~0.1 μm. The surface morphologies of both the AlN buffer and the top GaN layer were examined by Nomarski microscopy. The layers were featureless and mirror-like, as expected for 2D layers. The non-intentionally doped GaN epilayer was *n*-type with $n \sim 5 \times 10^{17}$ cm^{-3}, as determined from capacitance-voltage (*C-V*) measurements.

In addition to the *n*-GaN epilayers grown on Si(111), we have recently grown *p-n* structures on sapphire. Following a 0.4 μm AlGaN buffer layer and a 1 μm layer of unintentionally-doped GaN, a 0.5 μm GaN:Mg layer was grown. From *C-V* measurements, $p \sim 2 \times 10^{17}$ cm^{-3}. X-ray diffraction measurements, shown in Figure 1, using a Philips MRD diffractometer indicated good crystal quality, with a 270 arcsec ω-2Θ scan FWHM and a 589 arcsec ω-scan FHWM (the latter measurement taken with the receiving slit removed from the proportional counter).

The process flow for the fabrication of diodes along with the schematic cross section of a Schottky diode are shown in Figure 2. Fabrication of vertical geometry diodes with dimensions ranging from 50 μm^2 to 500 μm^2 began with the definition of mesas by reactive ion etching (RIE) using, typically, 10 sccm Cl_2 at 10 mTorr and 200 W rf power. Photoresist was used as the etch mask. As shown in Figure 3, etching of the GaN/Si(111) structures at rates of ~0.13 μm/min resulted in mesa structures exhibiting anisotropic profiles, smooth sidewalls, and a smooth surface morphology. By contrast, Cl_2 RIE of the GaN/Al_2O_3 structures exhibited rough sidewall and surface morphologies. Measurements of average roughness R_a during 500 μm scans using a Tencor Alphastep 500 indicated R_a was 44Å for the unetched surface and 106Å for the etched surface.

Ohmic contacts to *n*-GaN were made with e-beam evaporated 30 nm Ti/70 nm Al/10 nm Ti/200 nm Au. The ohmic contacts were annealed at 600°C for 20 s in a nitrogen ambient. The

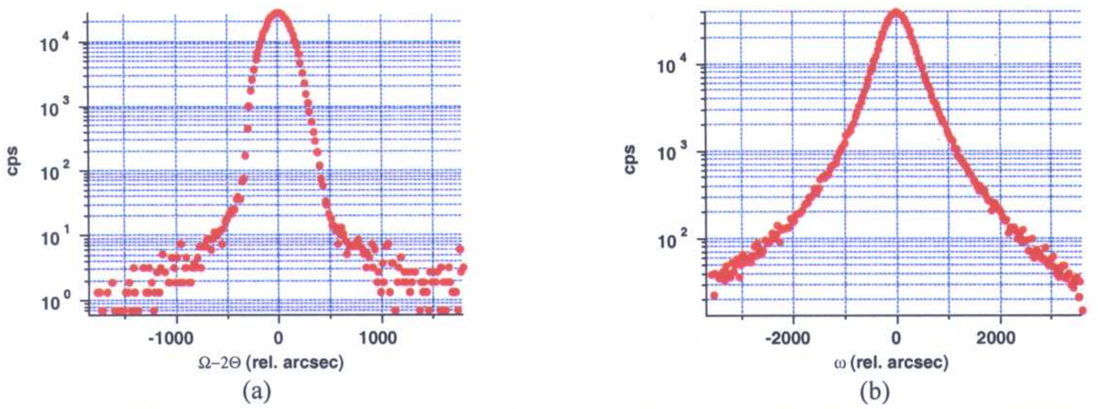
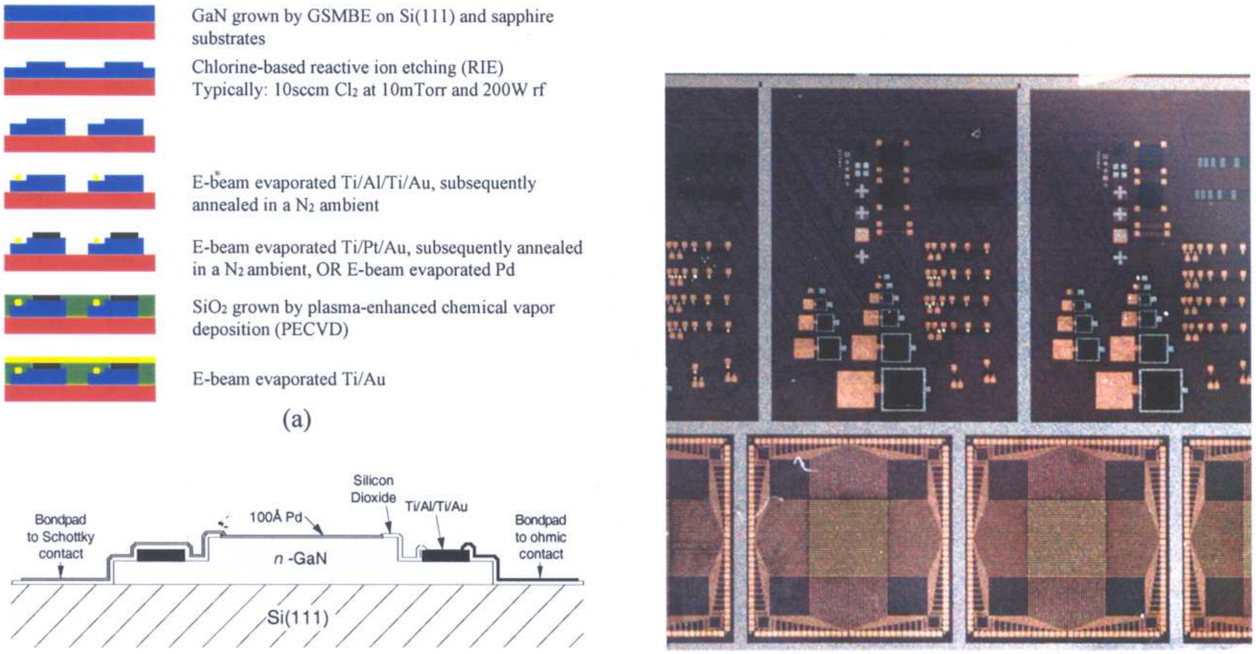


***Figure 1**. X-ray diffraction measurements show good crystal quality for a p-n structure grown on sapphire. (a) ω-2Θ scan with FWHM 270 arcsec, and (b) ω-scan with FWHM 589 arcsec.*



(b) (c)

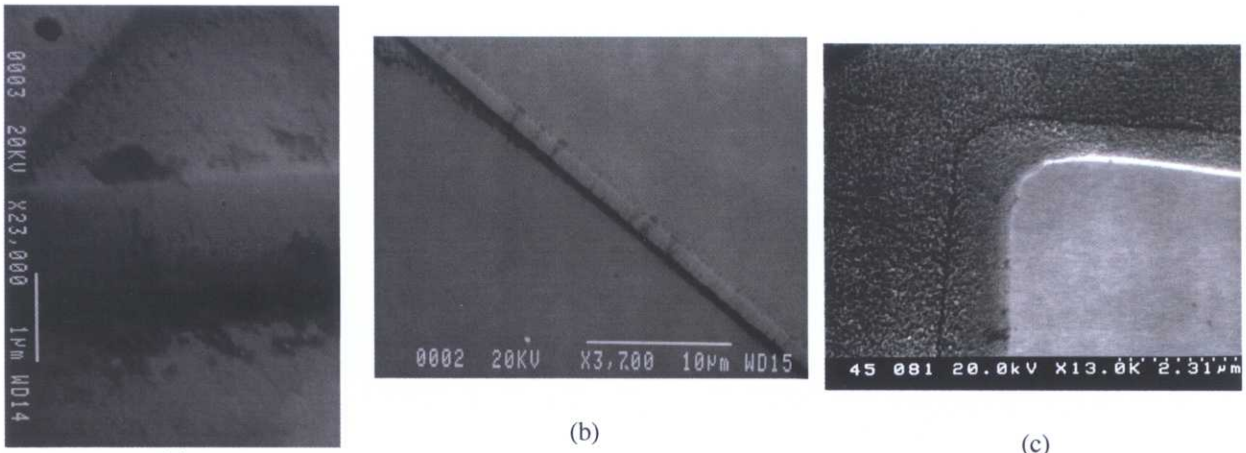
Figure 2. (a) Process flow for diode fabrication. Note that the PECVD SiO_2 is actually a conformal film, as shown explicitly in (b), the schematic cross section of the Schottky diode structure. In neither (a) nor (b) do we depict the AlN or AlGaN buffer layers explicitly. (c) Detail of a fully processed wafer incorporating both single-element detectors and detector arrays.

top, semitransparent Schottky barrier was formed by a standard liftoff technique using e-beam evaporated 10 nm Pd. For the *p-n* diodes, the *p*-metallization was Ti/Pt/Au, which has been shown to produce low-resistance contacts to *p*-GaN[9]. However, transfer length method (TLM) measurements performed on our samples, and displayed in Figure 4, showed a high specific contact resistance of $3.2 \times 10^{-1}\ \Omega\text{cm}^2$. For photodiode applications in which the junction resistance is very large, this high contact resistivity is probably not a great concern. A 0.1 μm SiO_2 layer was subsequently grown by plasma enhanced chemical vapor deposition (PECVD) to provide both surface passivation and electrical isolation between ohmic and Schottky contacts. Windows over the Schottky electrodes were then defined in the SiO_2 layer using standard CF_4/O_2 RIE. Finally, Ti/Au bondpads to the electrodes were deposited.

Current-voltage (*I-V*) characteristics were obtained with a Keithley 617 electrometer and the noise characteristics of the photodiodes were measured in the frequency range of 1 Hz–1 kHz using low-noise current and voltage preamplifiers and a fast Fourier transform spectrum analyzer[4, 10].

RESULTS

Current-voltage (*I-V*) characteristics of an $86 \times 86\ \mu\text{m}^2$ Pd/*n*-GaN/Si(111) Schottky diode are shown in Figure 5(a). Assuming thermionic emission and an effective Richardson constant $A^{**} = 24\ \text{A cm}^{-2}\,\text{K}^{-2}$, the Schottky barrier height was determined from the forward-bias *I-V*s to be 0.9–1.1 eV, in agreement with reported results[11, 12]. The dark current at –2V bias is $2.10 \times 10^{-8}\ \text{A/cm}^2$. To our knowledge, this is the lowest dark current density reported for any GaN-based diode on Si(111). Also shown in Figure 5(a) are the *I-V* characteristics of the diode



(a) (b) (c)

Figure 3. *(a) and (b) show a mesa defined by Cl_2 RIE in n-GaN/Si(111). The etched surface and mesa sidewall exhibit smooth morphology. In (a) some organic debris remains from the photoresist mask; the diagonal line at the top left of the figure is a crack in the epilayer. (c) By contrast, mesa defined by Cl_2 RIE in p-n GaN/Al_2O_3 results in rougher etched surface.*

under ultraviolet illumination (Electro-Lite BONDWand™ 81002 with emission between 320–380 nm, peaked at 350 nm and a light output ~20 mWcm^{-2} at 350 nm). We present this data only to demonstrate UV sensitivity of the Schottky diodes. In Figure 5(b), we display the *I-V* characteristics of a 50×50 μm^2 single-element *p-n* diode. The dark current density is quite low, though larger than that of the Schottky diodes on Si(111). We tentatively attribute the increased dark current to leakage paths associated with the poor sidewall morphology.

Noise power spectra for a Schottky diode on Si(111) for different values of the reverse bias are shown in Figure 6(a). The noise is $1/f$ limited, as is common for Schottky barrier GaN detectors at low frequencies. The zero-bias noise spectral density measured at 1 Hz is 9×10^{-29} A^2/Hz. To our knowledge, this is the lowest noise spectral density reported for GaN photodetectors on Si(111). Measurements of the noise power density as a function of diode current are shown in Figure 6(b). Comparison of this data with the theoretical value of the shot noise ($I_{shot} = (2eI)^{1/2}$) indicates that the diode is not shot noise limited and is consistent with $1/f$ noise being the dominant contribution to the noise power density in this frequency regime. The surface passivation provided by the SiO_2 layer probably contributes to both the low reverse bias dark current and low noise power density. Other researchers have found plasma-deposited SiO_2 films on *n*-type GaN to exhibit low interface trap densities[13, 14].

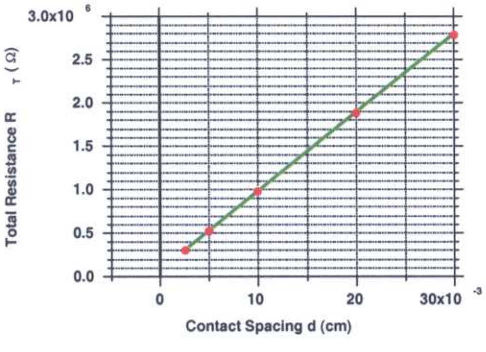
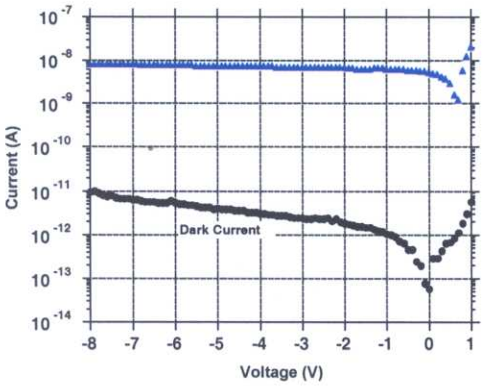
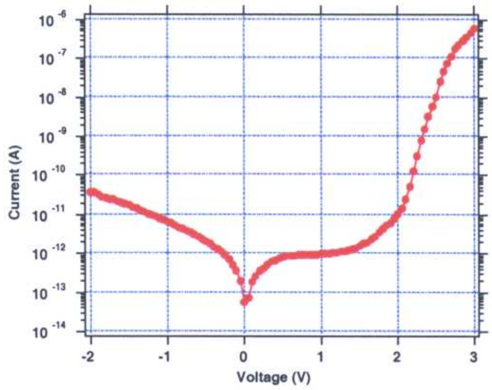


Figure 4. *TLM measurements of Ti/Pt/Au ohmic contacts to p-GaN show a specific contact resistivity of 3.2×10^{-1} Ωcm^2. The green line is a linear fit to the experimental data.*



(a)



(b)

Figure 5. (a) . I-V response of an 86 (86 μm^2 single-element, Schottky-barrier detector. The dark current density at -2 V bias is 2.10×10^{-8} A/cm^2. The top curve shows the I-V under UV illumination. (b) I-V response of a 50×50 μm^2 single-element, p-n diode. The dark current density at -2 V bias is 1.6×10^{-6} A/cm^2.

CONCLUSIONS

We have reported on mesa-isolated Schottky diodes fabricated from n-GaN epilayers grown by gas-source molecular beam epitaxy (GSMBE) on Si(111) that exhibit extremely low noise and dark current The dark current density and zero-bias noise spectral density of an 86×86 μm^2 single-element detector are, to our knowledge, the lowest values of these parameters reported for GaN diodes on silicon. We believe these results suggest that photodetectors based on GaN/Si(111) may possess many of the attributes required of space astronomy applications. In addition, we have presented preliminary results for *p-n* diodes fabricated from epilayers grown by GSMBE on sapphire.

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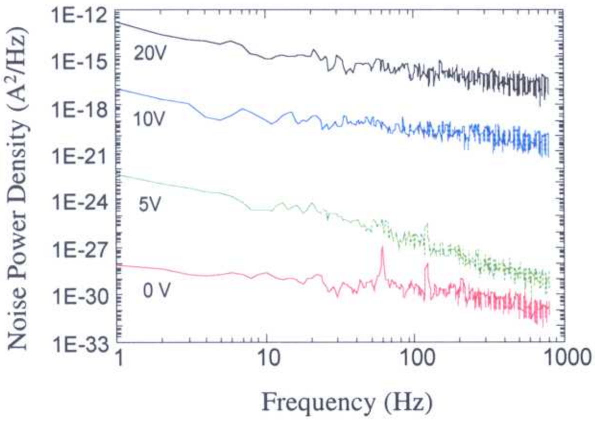
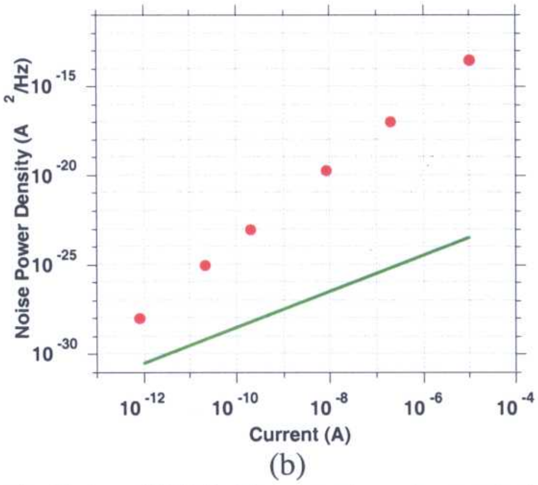


(a)



(b)

Figure 6. *(a) Noise spectral density measurements of a Schottky diode on Si(111). The zero-bias noise spectral density measured at 1 Hz is 9×10^{-29} A^2/Hz, and 1/f noise is the dominant low-frequency noise mechanism. (b) Comparison of measurements of noise power density versus current with the theoretical value of the shot noise (green line) show the diode is not shot-noise-limited.*

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